Degradation of Solar Cells Due to Arcing in a Vacuum Chamber

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Degradation of Solar Cells Due to Arcing in a Vacuum Chamber

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This report summarizes the senior project entitled Degradation of Solar Cells Due to Arcing in a Vacuum Chamber. The goal of this experiment was to show electrical and physical degradation of silicon solar cells in a vacuum chamber. The cells were characterized and then placed in a vacuum chamber. Under vacuum, a potential was created to induce arcing to the cell. The cell was characterized again after arcing to determine the change in efficiency. This document details the process for designing the circuit to create the arcing, and the different setups used to degrade the cells electrically and physically. It also describes the final setups to be used in the lab write-up for the Aerospace Engineering Department's Spacecraft Environment Laboratory.

Nomenclature

A_p	=	Area of ;late (m^2)
C	=	Capacitance (C)
E	=	Energy (J)
I	=	Adjusted current (A)
I_0	=	Saturation current (A)
I_l	=	Applied current (A)
P_{max}	=	Maximum output (W)
P_{in}	=	Energy from the sun (W)
T	=	Temperature (K)
V	=	Voltage (V)
d	=	Plate distance (m)
k	=	Boltzmann's constant (J/K)
q	=	Elementary charge (C)
ε	=	Vacuum permittivity (μF/m)
η_{max}	=	Maximum efficiency

I. Introduction

SPACECRAFT must design their system with the knowledge that there will be degradation due to the space environment. There are many different possibilities for degradation, electrostatic discharge (ESD) being one of them. ESD, a type of arcing, is the transfer of electrostatic charge between objects at different potentials. Charging anomalies have been a recognized problem for spacecraft since the 1950s. They are caused by the accumulation of electrical charge from the space environment. Effects of this charging can range from disruption of simple processes to a total mission failure. Charging can either be of the spacecraft as a whole, or different portions of the spacecraft. Charging of the spacecraft as a whole creates a potential difference relative to the environment. Charging across the surfaces of the spacecraft can cause arcing from one part of the spacecraft to another.[1]

The plasma environment of space can cause charging of a spacecraft. A plasma, "can be defined as a gas of electrically charged particles in which the potential energy of attraction between a typical particle and its nearest neighbor is smaller than its kinetic energy."[2] Basically, it is made up of ions and electrons (charged particles). These charged particles can build up on surfaces and thereby charge the spacecraft. Solar arrays are of particular concern

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because of the proximity of the dielectric coverslides to the metallic interconnects. An ESD caused by charging can affect the electronics of the solar array as well as erode the surface.[2] This damage affects the possible output of the solar array to the spacecraft, requiring engineers to design for a lower end-of-life (EOL) output.

This experiment attempts to show electronic and physical degradation of solar cells due to arcing in a vacuum. Knowing that arcing does occur in space, the focus was on the actual degradation caused by the arcing and not exactly recreating circumstances in space. It shows the difference in degradation for different setups to show how the design of a solar array can affect its potential degradation.

II. Analysis

There were several factors that needed to be planned before performing tests. There needed to be a plan for creating the arc, a way to test the degradation of the cells, and a plan for different setups.

A. Inducing Arcing

In order to cause arcing in the chamber, plasma needed to be generated. In order to do that, a potential difference needed to be created to ionize the particles in the chamber. Using an energy storage capacitor in parallel with an anode, the high breakdown voltage and arc current could be provided by the same supply.[3] The charge for the capacitor would be provided by a high voltage supply. To limit the current out of the supply, a relatively large resistor was placed in series with it. To set the level and duration of the arc, a small resistor was placed in series from the capacitor to the anode. To ensure arcing to the solar cell, it needed to be biased by either the anode or the cathode. Both cases were tested in this experiment. A simple anode cathode plate setup, with the cathode grounded to the chamber and the anode charged by an external circuit was used. The potential difference between the plates would cause the ionization of the particles between them until breakdown occurred. The final setup is shown in Figure 1 where the solar cell position was either the cathode or the anode depending on the test.

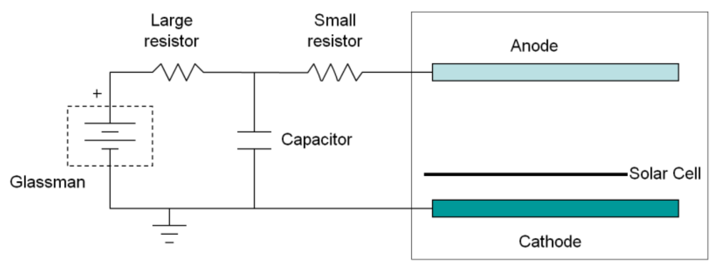

Figure 1. Setup for arcing test. The box around the Anode, Cathode, and Solar Cell represents the vacuum chamber.

The capacitance and resistance of the circuit were determined based on a combination of available components and energy expected for discharge. A higher energy of course would mean more damage to the cells. The equation for energy is

$$E = \frac{1}{2}CV^2 \tag{1}$$

where E is the energy, C is the capacitance, and V is the voltage. For the Paschen breakdown, the capacitance was determined using the following equation

$$C = \frac{\varepsilon A_p}{d} \tag{2}$$

where ε is the vacuum permittivity (8.854x10^{-12}μF/m), A_p is the area of the plate, and d is the distance between the plates. Based on previous experiments, performed in the Cal Poly Space Environments Lab in the Winter of 2012, the breakdown voltage was expected to be between 580 and 650V. The largest capacitor available was 2μF. This meant an expected energy of between 0.336 and 0.423J for this experiment. The duration of the arc would also be a significant factor in damage to the cells. The longer the cell is subjected to the arc, the more damage it will incur.

The large resistor used was 20,000Ω, the small resistor was 100Ω, and the capacitance was either 2μF or 4μF depending on the test.

B. Measuring Degradation

By characterizing the solar cell before and after arcing, the degradation of the electronics in the cell can be shown. To do this, the cell was placed in direct sunlight and a DC Load was used to supply a current to the cell. By varying the current and reading the voltage produced, the current voltage characteristics of the cell were established**Error! Reference source not found.**. By multiplying the current and voltage at the knee of the curve, the max power can be calculated. Comparing the maximum power before and after arcing will show the degradation of the cell.

Silicon solar cells were used for this experiment. To measure the I-V characteristics, wires were soldered onto the cells to create leads. The load was connected to the cell, and a voltmeter was connected in parallel. The cell was setup so that it was directly facing the sun, and the ambient temperature of the cell was taken multiple times throughout data collection. The temperature affects the efficiency of the cell, so when comparing before and after, this could have an impact on the results. To avoid this, the current was adjusted using the following equation.

$$I = I_l - I_0 \left(e^{\frac{qV}{kT}} - 1 \right) \tag{3}$$

where I is the adjusted current, I_l is the current applied, I_0 is the saturation current of the diode (1.95×10^{-12} A/m^2)[4], q is the elementary charge (1.6×10^{-19}C), k is Boltzmann's constant, T is the temperature in Kelvin, and V is the measured cell voltage.[5]

To determine the amount of degradation, the I-V characteristics of the cell were used to determine the efficiency of the cell before and after arcing. Efficiency was calculated using

$$\eta_{max} = \frac{P_{max}}{P_{in}} \tag{4}$$

where η_{max} is the maximum efficiency of the cell, P_{max} is the maximum possible output of the cell, and P_{in} is the product of the irradiance of the light from the sun and the area of the solar cell.

C. Parameters to Change

To see the variance of degradation possible, several paramaters were varied. The bias of the solar cell, anode vs. cathode, and orientation, facing plate vs. plasma would affect how the cell was being damaged. Cathode material would affect the breakdown voltage of the circuit which would change the energy applied to the cell. Increasing the capacitance used in the circuit would increase the energy applied to the cell. Increasing the time would increase the degradation as well. Changing from high voltage to Paschen would lower the breakdown voltage and increase the damage as well.

III. Testing

Four series of tests were performed for this experiment. Each series took the results from the previous series' and expanded or improved them. Data from the Winter 2012 lab experiment at Cal Poly was used as a reference for initial test planning.

D. Previous Tests

The tests run in the Winter of 2012 showed that with the solar cell cathode biased, two minutes of arcing was enough to completely destroy the cell. No voltage could be produced across the cell after arcing. With this information, the new test would lower the time to cause less damage. Paschen breakdown at two minutes caused significant damage, but did not destroy the cell. With the cell on the anode, the degradation is not as significant, but can still be seen, and is more significant with the cell facing the anode than with the cell facing away.

E. First Series of Tests

The first set of tests was performed on initially planned to be performed Friday, May 11th, but due to difficulties with the chamber, they were postponed to Sunday, May 13th. Each test one of the aforementioned paramaters. The following table, Table 1, summarizes the setups. Each setup was placed in a

Table 1. Summary of first series of test paramaters.

Test #	Cathode Material	Cell Orientation/Bias	Arc Time	Circuit Capacitance
1	Copper	Away/Anode	2 mins.	2μF
2	Stainless Steel	Away/Anode	2 mins.	2μF
3	Stainless Steel	Away/Cathode	1 min.	2μF
4	Stainless Steel	Toward/Anode	2 mins.	2μF
5	Stainless Steel	Away/Anode	1 min.	Paschen

The first test produced low frequency of arcing with an unexpected glow around the cathode. There was degradation to the cell, but not much effect on the efficiency of the cell. The visual effects, however, were significant.

For the second test, the copper cathode was switched to stainless steel. It had lots of arcing with no glow and the degradation affects were about the same. The third test biased the solar cell to the cathode instead of the anode; it had lots of arcing in the chamber, and showed significant degradation to the cell characteristics. Test four oriented the anode biased cell to face the anode and also had lots of arcing similar to test two. The last test in this series was a Paschen breakdown with the cell biased to the anode the plan had initially been to bias it to the cathode, but this was forgotten until the arcing had been completed. The circuit was bypassed by disconnecting the capacitor and resistors. There was not a lot of arcing seen in this test, but there was degradation to the cell.

This first series of test produced a mix of desired and undesired effects, leading to a decision for a higher plasma density. This was to be done by increasing the capacitance. It was also decided to repeat tests one and five with the cell cathode biased, and test two with a longer arc time.

F. Second Series of Tests

The second set of testing was performed on Monday, May 14th. Due to time constraints, only two test were run in this series. Table 2 summarizes the setups.

Table 2. Summary of second series of test paramaters.

Test #	Cathode Material	Cell Orientation/Bias	Arc Time	Circuit Capacitance
6	Stainless Steel	Away/Anode	2 mins.	4μF
7	Stainless Steel	Toward/Anode	2 mins.	4μF

This series of test was a mix of good and bad. Test six achieved breakdown and had what appeared to be minimal arcing. After checking the efficiency of the cell, however, it was a successful test. After reaching breakdown, test 7 had a minimal amount of arcing that did not continue for the allotted two minutes. The reason for this was not determined, but it may have been due to poor circuit connection. The cell used for test 7 was broken before post-arcing data could be collected and therefore needed to be repeated. The conclusion of this series was to repeat the test, verifying that the setup was correct before pulling vacuum, and taking extra care not to break any cells.

G. Third Series of Tests

Wednesday, May 23rd was the test day for the third series of tests. The goal was to repeat the necessary test from series two, and perform the desired tests determined after series one. A summary is shown in Table 3.

Table 3. Summary of third series of test paramaters.

Test #	Cathode Material	Cell Orientation/Bias	Arc Time	Circuit Capacitance
8	Stainless Steel	Toward/Anode	2 mins.	4μF
9	Stainless Steel	Away/Cathode	1 min.	Paschen
10	Stainless Steel	Away/Anode	3 min.	2μF
11	Copper	Away/Cathode	1 min.	2μF

The tests in this series appeared at first to have all gone perfectly. To avoid the problem of a misconnection, the voltage supply was turned on before pulling vacuum to check the potential across the electrodes. Everything was working as expected: breakdown voltages, lots of arcing for the desired time, and visible degradation for the anode biased cells. Unfortunately, after checking the I-V characteristics of the cells after arcing, it was determined that tests 8 and 11 did not have any electrical degradation. It is unclear why this happened. It's possible that the arcs were missing the cell; hitting the wires or the exposed part of the plate. Fortunately, tests nine and ten did show the desired electrical degradation.

H. Fourth Series of Tests

The last series of tests was solely to fix the experiments that did not work in series three. These tests were performed Sunday, May 27th and the setup summary is shown in Table 4.

Table 4. Summary of fourth series of test paramaters.

Test #	Cathode Material	Cell Orientation/Bias	Arc Time	Circuit Capacitance
12	Copper	Away/Cathode	1 mins.	2µF
13	Stainless Steel	Toward/Anode	2 mins.	4µF

This time, there didn't appear to be as much arcing as the first time these tests were run, but the characterization of the cells showed degradation.

IV. Results and Discussion

Each setup tested successfully showed electrical degradation, and many of them showed the physical degradation as well. Table 5 summarizes the results for each test. You can clearly see for tests eight and eleven how there was an error with the experiment. A negative percent difference means that their performance improved which must be error in the characterization of the cells.

Table 5. Summary of testing results.

Test #	Breakdown Voltage (V)	Energy (J)	% Efficiency Before	% Efficiency After	% Difference
1	622	0.387	8.75	8.01	8.50
2	600	0.360	9.24	8.65	6.36
3	593	0.352	8.91	2.03	77.2
4	587	0.345	9.34	8.83	5.43
5	538	$5.72\text{x}10^{-8}$	9.23	8.92	3.38
6	586	0.687	8.65	4.95	42.7
8	650	0.845	7.75	8.54	-10.2
9	589	$6.86\text{x}10^{-8}$	8.73	1.33	84.8
10	598	0.358	6.84	4.51	34.1
11	616	0.379	8.19	8.77	-7.08
12	608	0.370	7.70	7.44	3.36
13	588	0.691	7.91	7.21	8.89

It appears that for stainless steel, having the cell be cathode biased increases the degradation caused by the arcing. This is likely because when the cell is anode biased, it collects electrons until breakdown where it releases those electrons and begins to get bombarded with the electrons that had been collecting. These electrons are much smaller than ions and so have more energy; they cause many small impacts on the surface of the cell. This affects the surface properties more than the electronics. The cathode biased cells receive more concentrated ion impacts that should have a greater affect on the surface properties and the electrical components; this can be seen in the data shown above. There is a 77.2% loss in efficiency for the cathode biased cell of test three, but only a 6.36% loss for the anode biased cell of test two which had twice the arcing time. This same effect was not seen in the test with the Copper anode. The drop for the cathode biased cell was only 3.36% compared to the anode difference of 8.5%. This could be due to the glow discharge that occurred in the first test and would be something that could be improved upon in this experiment.

The next comparison is of the capacitance of the circuit. Increasing the capacitance will increase the plasma density by creating a higher potential between the plates. Tests two and six demonstrate the significant difference in degradation that it translates to. However, the same does not appear true for tests four and twelve. The difference between these two tests and the previously mentioned two is that the cells were connected facing the electrodes. However, the higher capacitance of the circuit did not have as great an impact as expected. This must mean that the primary cause for degradation must be the front of the cell. Electrons between the anode and the cell do cause damage to the back of the cell, you can see what it does in Figure 2. However, the capacitance should have a bigger impact on the efficiency.

Comparing the first two tests, one can see the difference between a copper cathode and a stainless steel cathode with the cell anode bised. Breakdown voltage for the copper plate is higher, making the energy higher and the degradation as well. This trend should also have been seen comparing tests three and twelve. However, there may have been an error in the setup that messed up the data.

Time was the last parameter that was varied for this experiment. The longer the cells are exposed to arcing, the more damage would ocurr. This is shown in comparing tests two and ten. Looking at the difference in efficiency, it is clear that exposure duration plays a large part of solar cell degradation.

The most significant visual degradation was seen in tests one, ten, and thirteen. Images of these cells can be seen in Figure 2. The first, cell is from the initial setup with the copper cathode. This test had glow discharge around the

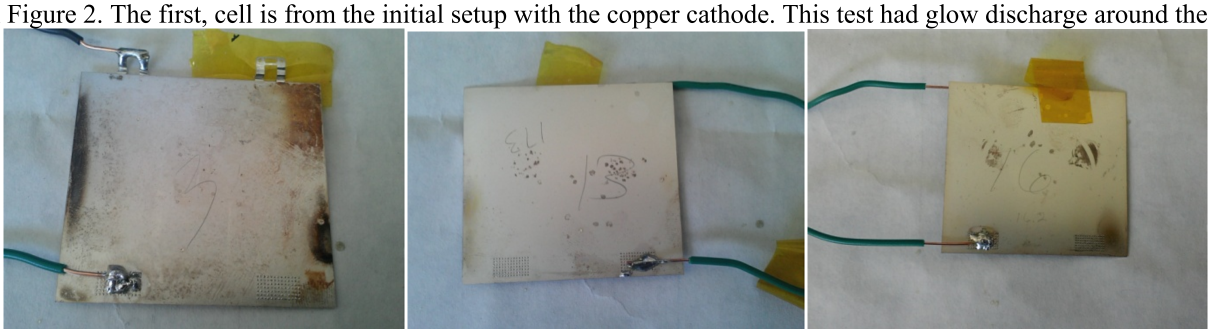

Figure 2. From left: cell from test one has dark black on the edges from the arcing; cell from test 10 has some yellowing along the left edge; cell from test 13 has a yellow black smudge in the bottom right corner.

cathode which could explain the blackening along the edges. The second cell was from test ten which was exposed to a long duration arc. The long exposure to a lower energy arc could explain the yellowing rather than blackening. The last cell was exposed to a higher energy but for a shorter time than the second. The higher energy led to a concentration of the electrons in one spot for the degradation. Each of these cells was anode biased. None of the cathode biased cells showed any significant degradation. Potentially, a much higher capacitance could cause more physical damage, however, a capacitance much higher than that used in this experiment would kill the electronics in the cell completely.

V. Conclusion

This senior project successfully demonstrated degradation of solar cells due to arcing. Through calculations and some trial and error, the experiment determined several factors that significantly affect the degradation of the solar cells. The information from this lab has been successfully used to design an experiment for the Aerospace Engineering Department’s Spacecraft Environments lab class. It was determined that the test setups for tests two, three, six, and ten would best benefit the lab class. Test two shows little degradation, and the other three show significantly more while only varying one thing. Since the lab already has a separate Paschen breakdown experiment, it was determined that those tests would not be used in the lab. To take this experiment to another level, one could introduce coverglass into the experimental design to make the lab more specific to spacecraft purposes.

Appendix

Appendix A

The following is a list of materials used in this experiment.

Table 6. List of materials, tools, and equipment needed for the testing of a solar cell in a single setup.

Materials	Tools	Equipment
Silicon solar cells	Soldering iron	Agilent system DC electronic load
Electrical wires	Wire cutters	Multimeter
Solder	Wire strippers	Temperature reader
Kapton tape	Scissors	Laptop
Plexiglass strip	Clamp stand	Glassman High Voltage Power Supply
Capacitors	Socket Wrenches	HVEC stainless bell jar vacuum chamber
Resistors	Screwdrivers	Anode-cathode plate assembly
		Granville-Phillips 275 Convectron gauge

Appendix B

Raw data from this experiment is included here:

Test 1 Current (A)	Voltage Before (V)	Voltage After (V)	Test 2 Current (A)	Voltage Before (V)	Voltage After (V)	Test 3 Current (A)	Voltage Before (V)	Voltage After (V)
0.01	0.932	0.93	0.01	0.948	0.941	0.01	0.944	0.541
0.02	0.933	0.931	0.04	0.94	0.933	0.04	0.946	0.506
0.04	0.945	0.926	0.07	0.933	0.923	0.07	0.926	0.468
0.05	0.936	0.924	0.1	0.925	0.913	0.1	0.915	0.424
0.07	0.936	0.917	0.13	0.926	0.904	0.13	0.908	0.388
0.1	0.931	0.91	0.16	0.917	0.885	0.16	0.9	0.353
0.12	0.927	0.907	0.17	0.917	0.882	0.19	0.899	0.318
0.15	0.915	0.893	0.18	0.917	0.878	0.22	0.885	0.281
0.16	0.92	0.888	0.19	0.917	0.875	0.25	0.879	0.236
0.18	0.909	0.879	0.2	0.913	0.874	0.28	0.863	0.196
0.19	0.913	0.873	0.21	0.909	0.872	0.3	0.847	0.176
0.21	0.901	0.866	0.22	0.905	0.871	0.31	0.844	0.155
0.23	0.895	0.859	0.23	0.898	0.867	0.32	0.839	0.145
0.24	0.885	0.857	0.24	0.892	0.864	0.33	0.837	0.133
0.26	0.88	0.85	0.25	0.885	0.86	0.34	0.837	0.127
0.27	0.881	0.847	0.26	0.88	0.857	0.35	0.83	0.112
0.29	0.865	0.839	0.27	0.874	0.854	0.36	0.819	0.102
0.3	0.856	0.837	0.28	0.869	0.851	0.37	0.816	0.086
0.31	0.847	0.827	0.29	0.866	0.845	0.38	0.805	
0.32	0.84	0.825	0.3	0.863	0.84	0.39	0.796	
0.33	0.828	0.814	0.31	0.86	0.834	0.4	0.786	
0.34	0.826	0.8	0.32	0.861	0.827	0.41	0.773	
0.35	0.825	0.792	0.33	0.861	0.82	0.42	0.77	
0.36	0.819	0.778	0.34	0.856	0.815	0.43	0.755	
0.37	0.812	0.766	0.35	0.85	0.809	0.44	0.74	
0.38	0.798	0.741	0.37	0.832	0.798	0.45	0.709	
0.39	0.792	0.74	0.39	0.811	0.778	0.46	0.67	
0.4	0.778	0.703	0.41	0.795	0.745	0.47	0.582	
0.41	0.753	0.663	0.42	0.781	0.732	0.48	0.5	
0.42	0.731	0.588	0.43	0.763	0.719	0.48	0.111	
0.43	0.682	0.45	0.44	0.743	0.687			
0.44	0.64	0.39	0.45	0.722	0.634			
0.45	0.603	0.299	0.46	0.682	0.491			
0.46	0.48	0.15	0.47	0.627	0.337			
0.47	0.42		0.47	0.627	0.26			
0.48	0.286		0.47	0.627	0.18			
0.49	0.112		0.47	0.627	0.107			
			0.48	0.49				

			0.49	0.113				

Test 4 Current (A)	Voltage Before (V)	Voltage After (V)	Test 5 Current (A)	Voltage Before (V)	Voltage After (V)	Test 6 Current (A)	Voltage Before (V)	Voltage After (V)
0.01	0.928	0.916	0.01	0.93	0.932	0.01	0.941	0.945
0.03	0.918	0.903	0.04	0.924	0.924	0.04	0.933	0.941
0.05	0.911	0.904	0.07	0.92	0.918	0.07	0.923	0.923
0.07	0.9111	0.901	0.1	0.915	0.91	0.1	0.913	0.91
0.09	0.902	0.893	0.13	0.904	0.903	0.13	0.904	0.896
0.11	0.907	0.888	0.16	0.888	0.889	0.16	0.885	0.868
0.13	0.89	0.88	0.19	0.879	0.878	0.17	0.882	0.865
0.15	0.894	0.871	0.22	0.873	0.871	0.18	0.878	0.843
0.17	0.885	0.865	0.25	0.86	0.863	0.19	0.875	0.829
0.19	0.871	0.86	0.26	0.859	0.857	0.2	0.874	0.825
0.2	0.864	0.851	0.27	0.853	0.86	0.21	0.872	0.787
0.21	0.86	0.847	0.28	0.845	0.856	0.22	0.871	0.775
0.22	0.857	0.844	0.29	0.84	0.842	0.23	0.867	0.715
0.23	0.855	0.839	0.3	0.834	0.841	0.24	0.864	0.644
0.24	0.851	0.834	0.31	0.84	0.83	0.25	0.86	0.642
0.25	0.845	0.831	0.32	0.838	0.824	0.26	0.857	0.606
0.26	0.841	0.825	0.33	0.839	0.818	0.27	0.854	0.555
0.27	0.835	0.818	0.34	0.84	0.818	0.28	0.851	0.47
0.28	0.836	0.809	0.35	0.833	0.807	0.29	0.845	0.446
0.29	0.833	0.803	0.36	0.828	0.796	0.3	0.84	0.376
0.3	0.827	0.795	0.37	0.812	0.789	0.31	0.834	0.295
0.31	0.816	0.784	0.38	0.804	0.784	0.32	0.827	0.241
0.32	0.807	0.78	0.39	0.797	0.778	0.33	0.82	0.155
0.33	0.797	0.775	0.4	0.792	0.764	0.34	0.815	0.08
0.34	0.79	0.77	0.41	0.778	0.746	0.35	0.809	
0.35	0.786	0.765	0.42	0.768	0.735	0.37	0.798	
0.36	0.782	0.759	0.43	0.752	0.708	0.39	0.778	
0.37	0.78	0.75	0.44	0.749	0.69	0.41	0.745	
0.38	0.767	0.741	0.45	0.738	0.671	0.42	0.732	
0.39	0.758	0.727	0.46	0.708	0.622	0.43	0.719	
0.4	0.745	0.714	0.47	0.69	0.517	0.44	0.687	
0.41	0.729	0.695	0.47	0.69	0.46	0.45	0.634	
0.42	0.724	0.683	0.47	0.69	0.36	0.46	0.491	
0.43	0.704	0.665	0.47	0.69	0.103	0.47	0.337	
0.44	0.693	0.643	0.48	0.633		0.47	0.26	
0.45	0.679	0.612	0.49	0.57		0.47	0.18	
0.46	0.659	0.571	0.5	0.43		0.47	0.107	
0.47	0.639	0.52	0.5	0.108		0.48		
0.48	0.614	0.349						
0.48	0.614	0.109						
0.49	0.544							
0.5	0.505							
0.51	0.3							
0.51	0.15							

Test 8 Current (A)	Voltage Before (V)	Voltage After (V)	Test 9 Current (A)	Voltage Before (V)	Voltage After (V)	Test 10 Current (A)	Voltage Before (V)	Voltage After (V)
0.01	0.966	0.976	0.01	0.972	0.902	0.01	0.986	0.923
0.03	0.959	0.965	0.03	0.968	0.857	0.03	0.982	0.913
0.05	0.956	0.958	0.05	0.964	0.777	0.05	0.978	0.891
0.07	0.952	0.952	0.07	0.95	0.685	0.07	0.973	0.873
0.09	0.946	0.954	0.08	0.9555	0.515	0.09	0.965	0.85
0.11	0.94	0.953	0.09	0.961	0.332	0.11	0.957	0.824
0.13	0.933	0.945	0.09	0.961	0.237	0.13	0.957	0.792
0.15	0.926	0.932	0.09	0.961	0.102	0.15	0.954	0.749
0.17	0.92	0.929	0.09	0.961	0.037	0.17	0.951	0.716

0.19	0.914	0.928	0.11	0.957		0.19	0.945	0.666
0.2	0.912	0.922	0.13	0.946		0.2	0.938	0.661
0.21	0.91	0.925	0.15	0.939		0.21	0.934	0.64
0.22	0.909	0.913	0.17	0.95		0.22	0.931	0.622
0.23	0.902	0.91	0.19	0.94		0.23	0.927	0.589
0.24	0.9	0.912	0.2	0.938		0.24	0.923	0.572
0.25	0.894	0.901	0.21	0.928		0.25	0.912	0.543
0.26	0.891	0.899	0.22	0.923		0.26	0.908	0.531
0.27	0.886	0.888	0.23	0.914		0.27	0.899	0.505
0.28	0.879	0.89	0.24	0.913		0.28	0.884	0.474
0.29	0.872	0.888	0.25	0.915		0.29	0.871	0.455
0.3	0.866	0.886	0.26	0.913		0.3	0.86	0.437
0.31	0.862	0.88	0.27	0.908		0.31	0.844	0.404
0.32	0.857	0.873	0.28	0.9		0.32	0.827	0.392
0.33	0.845	0.866	0.29	0.897		0.33	0.786	0.353
0.34	0.839	0.8625	0.3	0.894		0.34	0.755	0.34
0.35	0.836	0.859	0.31	0.877		0.35	0.718	0.314
0.36	0.825	0.847	0.32	0.869		0.36	0.68	0.294
0.37	0.814	0.832	0.33	0.86		0.37	0.625	0.267
0.38	0.791	0.827	0.34	0.859		0.38	0.534	0.236
0.39	0.783	0.813	0.35	0.851		0.39	0.504	0.217
0.4	0.757	0.801	0.36	0.849		0.4	0.43	0.19
0.41	0.733	0.794	0.37	0.846		0.41	0.358	0.164
0.42	0.697	0.782	0.38	0.831		0.42	0.308	0.145
0.43	0.613	0.764	0.39	0.818		0.42	0.237	0.133
0.44	0.54	0.745	0.4	0.797		0.43		0.113
0.44	0.43	0.729	0.41	0.783		0.44		0.096
0.45	0	0.712	0.42	0.77		0.46		
0.46		0.667	0.43	0.753		0.47		
0.47		0.616	0.44	0.725		0.48		
0.48		0.526	0.45	0.693				
0.49		0.24	0.46	0.624				
0.5		0	0.47	0.544				
			0.47	0.104				

Test 11 Current (A)	Voltage Before (V)	Voltage After (V)	Test 12 Current (A)	Voltage Before (V)	Voltage After (V)	Test 13 Current (A)	Voltage Before (V)	Voltage After (V)
0.01	0.991	0.976	0.01	0.99	0.99	0.01	0.969	0.966
0.03	0.983	0.981	0.03	0.993	0.988	0.03	0.975	0.964
0.05	0.979	0.976	0.05	0.989	0.984	0.05	0.972	0.95
0.07	0.979	0.976	0.07	0.993	0.981	0.07	0.965	0.941
0.09	0.976	0.965	0.09	0.984	0.978	0.09	0.963	0.939
0.11	0.971	0.973	0.11	0.978	0.974	0.11	0.956	0.931
0.13	0.956	0.963	0.13	0.977	0.971	0.13	0.942	0.924
0.15	0.948	0.959	0.15	0.973	0.968	0.15	0.94	0.916
0.17	0.948	0.955	0.17	0.968	0.9664	0.17	0.939	0.909
0.19	0.947	0.953	0.19	0.966	0.9648	0.19	0.93	0.902
0.2	0.944	0.951	0.2	0.965	0.964	0.2	0.927	0.898
0.21	0.948	0.946	0.21	0.963	0.959	0.21	0.921	0.89
0.22	0.947	0.947	0.22	0.957	0.955	0.22	0.919	0.886
0.23	0.943	0.95	0.23	0.949	0.95	0.23	0.912	0.879
0.24	0.939	0.948	0.24	0.95	0.95	0.24	0.906	0.877
0.25	0.937	0.94	0.25	0.95	0.941	0.25	0.906	0.869
0.26	0.934	0.939	0.26	0.945	0.938	0.26	0.901	0.861
0.27	0.931	0.935	0.27	0.943	0.934	0.27	0.897	0.853
0.28	0.927	0.931	0.28	0.945	0.931	0.28	0.889	0.8445
0.29	0.928	0.926	0.29	0.936	0.926	0.29	0.883	0.836
0.3	0.923	0.919	0.3	0.929	0.92	0.3	0.874	0.823
0.31	0.916	0.912	0.31	0.926	0.911	0.31	0.867	0.815
0.32	0.911	0.916	0.32	0.924	0.906	0.32	0.862	0.81
0.33	0.906	0.909	0.33	0.918	0.899	0.33	0.852	0.789
0.34	0.9	0.908	0.34	0.916	0.894	0.34	0.851	0.778
0.35	0.894	0.902	0.35	0.906	0.884	0.35	0.843	0.757

0.36	0.886	0.893	0.36	0.901	0.866	0.36	0.833	0.737
0.37	0.878	0.895	0.37	0.895	0.856	0.37	0.822	0.725
0.38	0.872	0.888	0.38	0.882	0.819	0.38	0.803	0.698
0.39	0.861	0.896	0.39	0.875	0.772	0.39	0.796	0.66
0.4	0.844	0.877	0.4	0.85	0.754	0.4	0.773	0.597
0.41	0.816	0.868	0.41	0.82	0.694	0.41	0.755	0.545
0.42	0.778	0.854	0.42	0.778	0.576	0.42	0.738	0.449
0.43	0.665	0.834	0.43	0.657	0.513	0.43	0.676	0.366
0.44	0.58	0.823	0.44	0.54	0.404	0.44	0.641	0.313
0.45	0.422	0.79	0.45	0.32	0.274	0.44	0.57	0.267
0.45	0.388	0.772	0.45	0.25	0.251	0.45	0.1	0.202
0.46		0.716	0.46	0.16	0.133	0.46	0	0.097
0.46		0.633	0.46	0.099	0.124	0.47		
0.47		0.605	0.47		0.099	0.48		
0.48		0.42	0.48			0.49		
0.49		0.103	0.49			0.5		

Appendix C

Matlab Code

```
clc
clear all
close all

load('OrgData')

e = 8.854*10^-12; %microF/m
A = 1.875*1.875*.00064516; %m^2 electrode area
a = 1.6*1.5625*.00064516; %m^2 cell area
d = 2*.0254; %m distance
I0 = 1.95*10^-12; %A/m^2 saturation current
q = 1.6*10^-19; % C elementary charge
k = 1.38*10^-23; % J/Kboltzmann's constant
P = 1361; % W/m^2 solar constant
%circuit capacitance
cap = [2*10^-6 2*10^-6 2*10^-6 2*10^-6 e*A/d 4*10^-6 4*10^-6 e*A/d...
    2*10^-6 2*10^-6 2*10^-6 4*10^-6]; % Farad
% breakdown voltage
bv = [622 600 593 587 538 586 650 589 598 616 608 588]; %Volts
% max power input from sun
Pin = P*a; % W

% arc energy
energy = .5.*cap.*bv.^2; % mJ

% Temperatures
T = 5/9.*([110 107  107 101.5 110 108 101 111 99.5 100 101.5 104 ...
    73 78 93 69 92 88 82 80 59 56 60 57]-32)+273; % K
% File adjustment
current(:,11) = [xlsread('May11_Test.xlsx',2,'A6:A44');zeros(5,1)];
voltage(:,11) = [xlsread('May11_Test.xlsx',2,'C6:C42');zeros(7,1)];

% Current adjustment for temperature
for i = 1:24
current(:,i) = current(:,i)-I0*(exp(q.*voltage(:,i)/(k.*T(i)))-1); % A
```

```
end

% pre-allocating
voltagea = zeros(44,12);
currenta = zeros(44,12);
voltageb = zeros(44,12);
currentb = zeros(44,12);

% Power
power = current.*voltage;

%Max power, splitting current and voltage into before and after vectors,
%calculating efficiency, plotting I-V characteristics
for i = 1:length(current(1,:))
    [maxpower(1,i) j] = max(power(:,i));
    maxcurrent(i) = current(j,i);
    maxvoltage(i) = voltage(j,i);
    eff(i) = maxpower(i)/Pin;
    if mod(i,2)==0
        currenta(:,i/2) = current(:,i);
        voltagea(:,i/2) = voltage(:,i);
        powera(:,i/2) = power(:,i);
        effa(i/2) = eff(i);
        maxpowera(:,i/2) = maxpower(:,i);
        maxcurrenta(i/2) = maxcurrent(i);
        maxvoltagea(i/2) = maxvoltage(i);
        figure
        plot(currentb(:,i/2),voltageb(:,i/2),'.',currenta(:,i/2)...
            ,voltagea(:,i/2),'.',maxcurrentb(i/2),maxvoltageb(:,i/2),'*'...
            ,maxcurrenta(i/2),maxvoltagea(:,i/2),'*')
        xlabel('Current(A)')
        ylabel('Voltage(V)')
        legend('Before','After','Max Before','Max After')
        if i <13
        title(['Test ',num2str(i/2)'])
        else
            title(['Test ',num2str(i/2+1)])
        end
    else
        currentb(:,(i/2+.5)) = current(:,i);
        voltageb(:,(i/2+.5)) = voltage(:,i);
        powerb(:,i/2+.5) = power(:,i);
        maxpowerb(:,i/2+.5) = maxpower(:,i);
        maxcurrentb(i/2+.5) = maxcurrent(i);
        maxvoltageb(i/2+.5) =    maxvoltage(i);
        effb(i/2+.5) = eff(i);
    end
end

% change in efficiency
ediff = (effb-effa)./effb;
eff

save('PowerData')
```

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